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MATHEMATICAL MODELLING OF FLAT AND LONG HOT ROLLING BASED ON FINITE ELEMENT METHODS (FEM)

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The aim of this paper is to critically assess the potential of mathematical modelling which uses finite element method software for solving operation problems in the hot rolling of flat and long products. We focused on concrete issues faced by rolling plants in the Moravian-Silesian region (Czech Republic). The investigation was always combined with field or pilot measurements or laboratory experiments.

Key words: steel, hot rolling, finite elements method (FEM), roll pass design, friction

Primjena metode konačnih elemenata (MKE) pri matematičkom modeliranju toplog valjanja plosnatih i šipkastih proizvoda. Cilj članka je kritička ocjena mogućnosti matematičkog modeliranja rabljenjem softvera metode konačnih elemenata pri tekućem razrješavanju problema toplog valjanja plosnatih i šipkastih profila. U konkretnom primjeru fokusirano je na tvrtke u Moravsko-Sleskom rejonu (Češka). Istraživanja su uvijek kombinirana pilot mjerenjima ili laboratorijskim eksperimentima.

Ključne riječi: čelik, toplo valjanje, metoda konačnih elemenata (MKE), kalibracija valjaka, trenje

INTRODUCTION

The main object of industrial research and development is to optimise the means of production for the manufacturing of a given product. The optimisation criteria may vary, depending on the requirements for the final product. In general, they should be based on full understanding of the manufacturing process. In forming processes, the knowledge of deformation mechanisms is crucial. Without knowing the impact of friction, material properties and tool geometry on the operation of the process, it is impossible to propose optimum shapes of tools, the configuration of machines, and to predict occurrence of defects and evolution of microstructure. Field (pilot) trials and physical modelling (laboratory rolling, forming simulators) alone cannot reveal the exact values of thermomechanical parameters and their distribution: e.g. the distributions of various parameters across the product cross-section are virtually impossible to determine. This is why process modelling using computer simulation has an increasing importance in today's metal forming processes [1-18].

SUMMARY OF KEY OUTCOMES

Our research provided a vast amount of results, all of which have been published in the form of conference talks or in professional journals. Our work comprises the following topics which may be classified with respect to the optimisation criterion as follows (the institutions where physical experiments were conducted are listed in the parentheses):

- ■ Friction in hot rolling:
  - □ Impact of friction coefficient on spreading of rolled steel products (Department of Materials Forming, VŠB-TU Ostrava (DMF), ŽDB GROUP a.s., Rolling mill, (ZDB)).

In this study, pilot rolling of 100×100 mm billet into 20 mm diameter bar in 13 passes was carried out. In each roll pass, a sample was taken and a cross-section print of the rolled bar was made. Simulations of individual roll passes were carried out for various friction values according to Tresca, ranging between 0.1-0.9. Other boundary conditions of the given roll pass remained the same. Comparison of the calculated cross-sections (see Figure 1) with the prints provided an as-

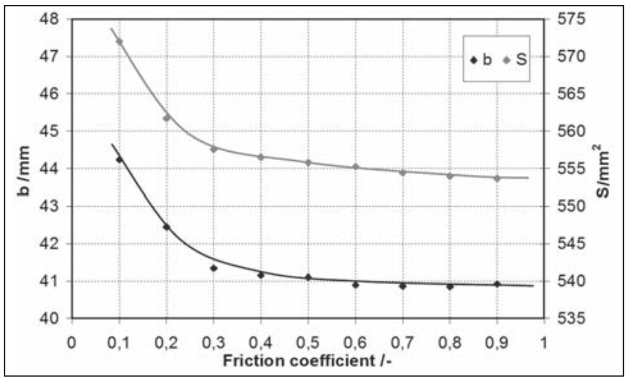

Figure 1 Dependency of the width b and the area S of the stock on various friction values in the roll groove R 20

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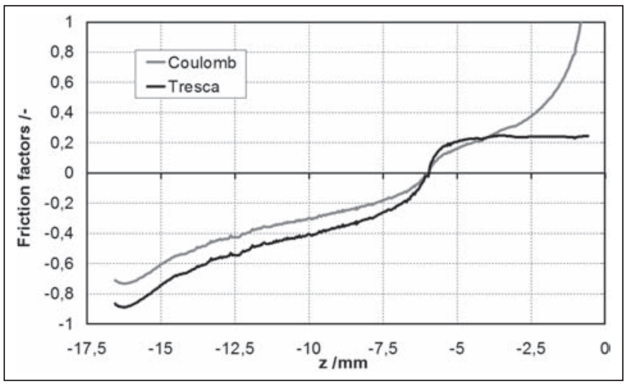

Figure 2 Dependence of Coulomb and Tresca friction factors on the distance from the plane of exit [20]

sessment of the optimal friction coefficient value for each roll pass [19].

□ Finding the friction coefficient value using inverse analysis of the rolled product shape (DMF).

The design and industrial application of a method of determining the friction coefficient and the friction factor along the arc of contact (see Figure 2) were based on the analysis of rolled product shape upon laboratory rolling. Results show that simplifying the mathematical model of rolling by using a constant value of friction may become one of the most significant sources of error [20].

■ Temperature field in a rolled product:

□ Cooling of shaped products in HCC rolling mill (ArcelorMittal Ostrava, a.s. (AMO)).

Inverse analysis (IA) principles were used for determining the temperature field upon rolling in shaped products as input data for subsequent computer simulation of cooling. The input parameter for IA was the dependence of the rolled product's surface temperature on time.

□ Definition of the temperature field in a rail upon rolling in VH rolling mill (Třinec Steelworks, a.s. (TZ)).

A method of determining temperature fields in rails and their exporting into FEM software for the purpose of heat treatment simulation was elaborated and verified

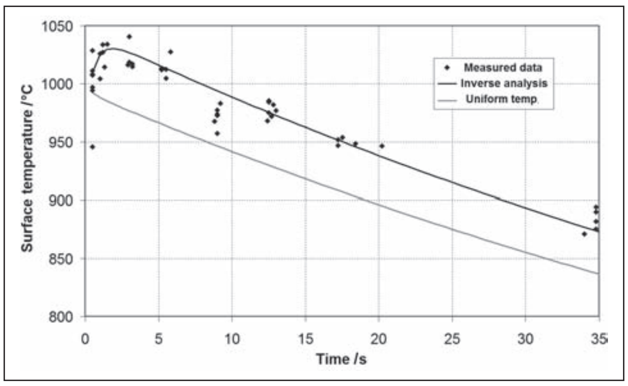

Figure 3 Measured surface temperatures and calculated cooling curves for a uniform temperature field (T = 1 000 °C) and for a temperature field computed using inverse analysis

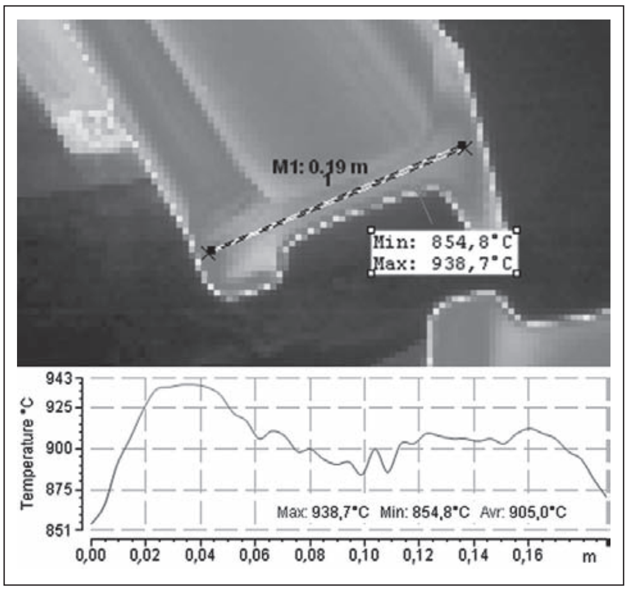

Figure 4 Analysis of a thermal image of the rail's cross-section after cutting off the rail's front end

in production. It relies on measuring the temperature field across the cross-section of the rail after cutting off its front end (see Figure 4). It is then described using a mathematical model with temperature variables associated with selected points on the rail's surface.

This method can be used in applications where the temperature field is very difficult to estimate (non-symmetric rolled products) and in those, where the full-scale FEM simulation of the rolling process becomes costly due to the process complexity.

A method of measuring temperature fields in rolled products (rails) by drilled thermocouples for laboratory simulation of heat treatment was designed and applied.

A hypothetical cooling process of rails in production was simulated by means of both above-mentioned methods. The simulation clearly showed that even the processes with in-line heat-treatment operations can benefit from equalizing the temperature field within a rail in a soaking furnace prior to the actual cooling. This can provide both higher hardness in the rail head and a less steep hardness gradient beneath the surface.

■ Evolution of microstructure in a rolled product:

□ Assessment of capabilities of controlled rolling in a medium section rolling mill (AMO).

Mathematical analysis of microstructure evolution in rolled 40×5 mm flat bar showed that in terms of microstructure, the current process is very close to the optimum setting. However, our analysis also revealed that in case of 40×60 mm sections, the finish rolling temperature cannot be controlled.

□ Obtaining the thermomechanical parameter vs. time dependences for rolling in HSC mill to be used as input data for plastometric experiments (heat treatment, DMF).

In pilot experiments with thermomechanical rolling of steel bars in the continuous fine section mill at TZ, non-homogeneity of microstructure and significant scat-

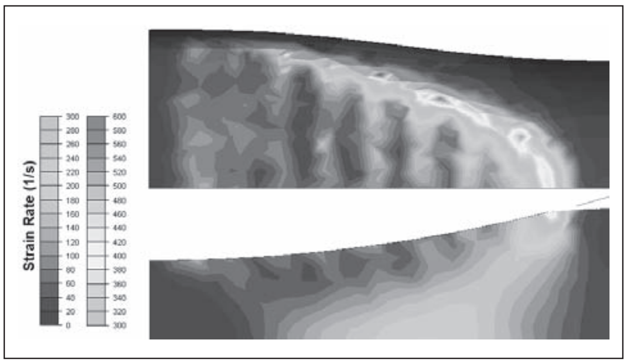

Figure 5 Distribution of strain rate across the cross-section and on surface – prefinishing stand, ASC rolling mill at TZ

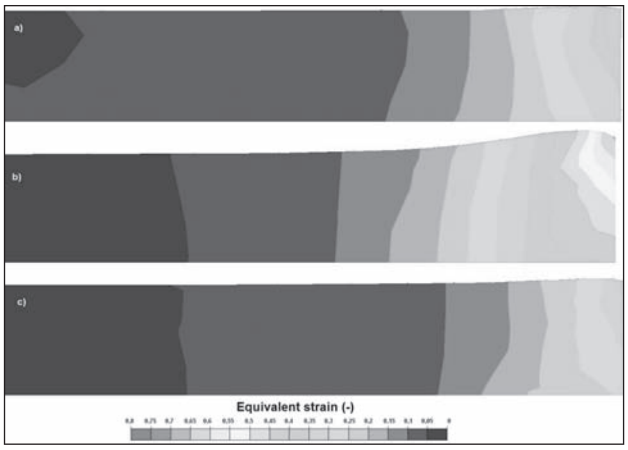

Figure 6 Dog bone shape and equivalent strain after vertical rolling: a) slab head b) middle of slab c) slab tail [22]

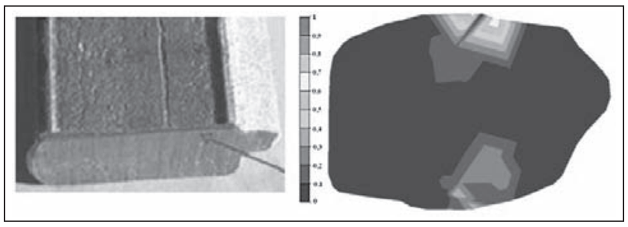

Figure 7 Left: defect in the final rolled product. Right: FEM simulation of the probability of lap occurrence caused by the wear of the first roll pass

ter in grain size across the bar's cross-section were revealed. FEM simulation was used as an efficient tool for describing the thermal-stress-deformation fields across the rolling gap. The main attention was devoted to mapping the strain rate (see Figure 5), strain and temperature. Changes in these quantities with time were mapped for various points on the cross-section of the rolled product. The data proved the non-homogeneity of deformation parameters across the section, which is due to the applied production technology.

- □ Construction of a new model for calculating the critical strain for onset of dynamic recrystallization and its verification in a laboratory rolling process (DMF).

Strain rates in the deformation zone in rolling of flat products were analysed in depth. Due to the presence of a region of inhibited deformation, the plot of strain rate vs. time for surface layers exhibits two peaks. The absolute value of strain rate of the first peak considerably exceeds the average value obtained using conventional formulas.

Taking into account this fact and upon an analysis of continuous plastometric experiments involving sharp changes in strain rate, a new model for calculation of critical strain for the onset of DRX has been constructed. The model was tested in laboratory rolling. The agreement between results of experiments, the new and the old model was by no means satisfactory, which applies in particular to the surface region of the rolled product. We attribute this to the additional effects which were impossible to incorporate in the mathematical analysis [21].

- ■ Final shape of rolled product:
- □ Impact of parameters of horizontal-vertical (H-V) rolling of slabs on the amount of scrap after rolling (DPM).

Mathematical analysis was successfully used for designing an H-V slab rolling process which uses the short-stroke method (see Figure 6) to significantly reduce the amount of scrap resulting from undesirable shapes of the slab ends [22].

Laboratory H-V rolling was carried out to verify the mathematical model. The process was also modelled using FEM analysis. The agreement between results for the shape of the product in its crucial part (the dog bone peak) is unsatisfactory. It was revealed that the mesh density is of great importance but, at the same time, other parameters (friction, surface undercooling, flow stress of the steel) have an impact on the dog bone shape. We did not succeed in obtaining the actual shape with sufficient accuracy [23].

- □ Clarification of causes of defects in rolling of a special section (Special Section Rolling Mill, VŮHŽ, a.s.).

FEM simulation confirmed our hypothesis that the defect (see Figure 7, left) is due to greater wear of the first box pass, which, in turn, causes greater spread and a higher probability of lap occurrence (see Figure 7, right). It turned out that mathematical modelling using FEM is very suitable for this type of task [24].

CONCLUSION

The present paper summarises the outcomes of FEM-based research into rolling processes. The combination of mathematical modelling methods with field or pilot testing or laboratory rolling is an important feature of this study. The following areas were explored: finding the friction coefficient value, modelling of temperature fields, modelling of microstructure evolution, and analysis of rolled product shape. The next part of this article will provide additional information on the assessment of formability of steels in the rolling process and development and use of a simulation program using rapid FEM algorithms.

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